The Effects of Proton Irradiation on SiGe:C HBTs

Shiming Zhang, Guofu Niu, John D. Cressler, Hans-Joerg Osten, Dieter Knoll, Cheryl J. Marshall, Paul W. Marshall, Hak S. Kim, and Robert A. Reed

***Abstract*--The effects of 63MeV proton irradiation on SiGe:C HBTs are reported for the first time. The dc characteristics and neutral base recombination of these SiGe:C HBTs are investigated for proton fluences up to 5×10^{13} p/cm^2. A comparison is made with SiGe HBTs fabricated in the same technology. Despite the fact that these SiGe:C HBTs degrade significantly during proton exposure, there is no indication that the carbon doping has any significant impact on the radiation response.**

I. Introduction

SiGe heterojunction bipolar transistor (HBT) technology has recently emerged as a contender for a wide variety of digital, analog, and RF applications in the 1-40 GHz range. One of the biggest challenges faced in sustained vertical profile scaling of SiGe HBTs is retaining the very narrow as-grown boron base profile within the SiGe layer during the post-epitaxial fabrication process. It was recently discovered by accident that the incorporation of low concentrations of carbon (< 10^{20} cm^{-3}) into the base region of a SiGe HBT can dramatically suppress boron outdiffusion (by 10×) [1], thus paving the way for further improvements in SiGe HBT performance. In essence, the vertical profile of the SiGe HBT can be thinned substantially by adding carbon without having to reduce the fabrication thermal cycles. This provides a tremendous advantage in technology scaling from a manufacturing viewpoint.

Recently, several successful demonstrations of C-doped SiGe HBTs (SiGe:C HBTs) have been reported [2]-[3]. These initial SiGe:C HBTs have shown excellent dc performance, peak f_T and f_{max} of more than 60 GHz, and ring oscillator delays below 20 ps [2]. Despite the fact that C is known to act as a deep trap in Si, no evidence to date suggests that C incorporation harms the SiGe HBT in any significant way. If SiGe:C HBTs are to become viable candidates for space electronics, clearly their radiation response must be carefully assessed. Of particular interest in this context is whether radiation exposure induces any unknown deleterious effects that can be associated with the C doping. In this work, the influence of proton irradiation on dc characteristics of SiGe:C HBTs, together with a comparison with SiGe HBTs fabricated in the same technology, are reported for the first time.

This work was supported by DTRA under the Radiation Tolerant Microelectronics Program, NASA-GSFC under the Electronics Radiation Characterization (ERC) Program, and the Auburn University CSPAE under contract # NCC3-511.

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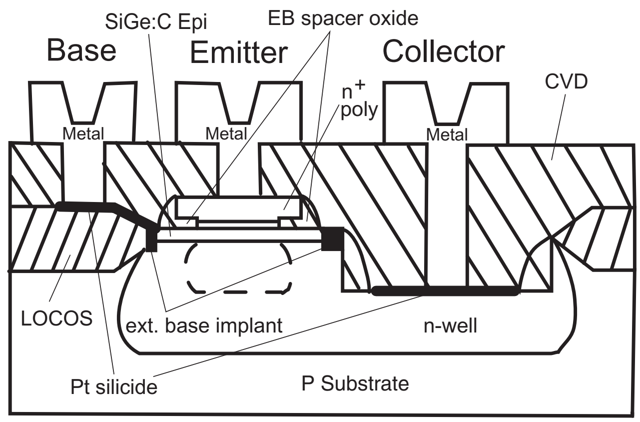

Fig. 1. Schematic cross-section of the SiGe:C HBTs.

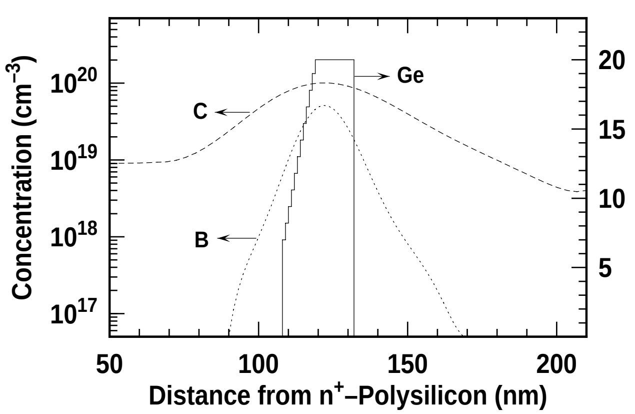

Fig. 2. A typical vertical profile of the SiGe:C HBTs, as measured by SIMS.

II. SiGe:C Technology and Radiation Experiment

The SiGe:C and SiGe HBTs investigated were fabricated at the Institute for Semiconductor Physics (IHP) in Germany.

This SiGe:C HBT process has an epi-free well and a single-polysilicon, self-aligned structure, as shown Fig. 1 [3]. The epi-free n-wells were produced by 500 keV phosphorus implantation following LOCOS formation. After annealing the well with a low thermal budget process, epitaxial layer stacks consisting of the SiGe:C base layer and a Si cap (right on top of the SiGe:C layer) were deposited by RT-LPCVD. The collector resistance can be adjusted by implantation through the emitter window without an additional masking step after SiGe/Si epitaxy (dashed line in Fig. 1). A special HBT construction featuring a minimized spacing between collector contact and internal transistor regions allows one to reach the low collector resistance necessary for high performance [3]. Fig. 2 shows a typical SiGe:C HBT vertical profile measured by secondary ion mass spectrometry (SIMS). The SiGe:C HBT has a thin, half-graded Ge profile and the C distribution with a peak concentration of about 10^{20} cm^{-3}. These SiGe:C HBTs have a measured peak f_T and peak f_{max} of 50 GHz and 70 GHz at V_{CE}=2 V, respectively, for a BV_{CEO}= 2.7 V [3], and are thus comparable in performance to IBM's first-generation 5HP SiGe HBT technology.

Samples were exposed to 62.5MeV protons at the Crocker Nuclear Laboratory cyclotron located at the University of California at Davis. The dosimetry measurements used a 5-foil secondary emission monitor calibrated against a Faraday cup. Ta scattering foils located several meters upstream of the target establish a beam spatial uniformity of 15% over a 2 cm radius circular area. Beam currents from about 5 pA to 50 nA allow testing with proton fluxes from 10^6 to 10^{11} protons/cm^2 /sec. The dosimetry system has been previously described [4]-[5] and is accurate to about 10%. At a proton fluence of 1×10^{12} p/cm^2, the measured equivalent gamma dose was approximately 136 krad(Si).

The samples were mounted on 28 pin dual in line packages with terminals floating and irradiated at normal incidence using four proton fluences: 1×10^{12} p/cm^2, 7×10^{12} p/cm^2, 2×10^{13} p/cm^2, and 5×10^{13} p/cm^2. Each package contained one SiGe:C HBT chip (of 8 mm $\times$ 4 mm size) and one SiGe HBT chip (of similar size), each with multiple transistors, for each proton fluence. The samples were measured at room temperature (T=300 K) before and after irradiation using an HP4155 Semiconductor Parameter Analyzer.

III. RESULTS AND DISCUSSION

In general, proton irradiation will produce generation/recombination (G/R) trapping centers, which effectively reduce the minority carrier lifetime, and hence degrade the current gain of the device [6-8]. In addition, ionizing radiation damage due to the charged nature of the proton flux will produce interface states and oxide trapped charges in the spacer oxide layer at the emitter-base space charge region [9]. In this paper, the effects of these traps and defects on the dc characteristics of SiGe:C HBTs and SiGe HBTs will be addressed.

Fig. 3 shows the effects of proton fluence on the forward Gummel characteristics. The base current degrades monotonically with increasing proton fluence, thereby causing a drop in the current gain. This is the conventional degradation mechanism observed in bipolar transistors. During irradiation the base current ideality factor in the low bias regime increases steadily from 1.10 to 1.67. Even at relatively high bias range of V_{BE}=0.6-0.8V, of relevance to most circuit designs, the base current ideality factor at a proton fluence of 5×10^{13} p/cm^2 is around 1.65, which indicates that a generation-recombination (G/R) is the principal component of the post-irradiated total base current. A plot of the excess base current $|I_{B,post}-I_{B,pre}|$ versus V_{BE} is shown in Fig. 4. In the low bias region (V_{BE}=0.2-0.4V), the ideality factors for the four curves are in the range of 1.6 to 1.7, while the ideality factors for the four curves correspond to 1.2-1.5 in the high bias region (V_{BE}=0.6-0.7V). Given that the slopes of the four curves for four proton fluences in Fig. 4 correspond to an ideality factor between 1 and 2 suggests that both G/R trapping centers in the bulk at the emitter-base space charge region and G/R trapping centers near the surface of the emitter-base spacer oxide at the emitter-base space charge region are responsible for the degradation of the base current after proton irradiation [6].

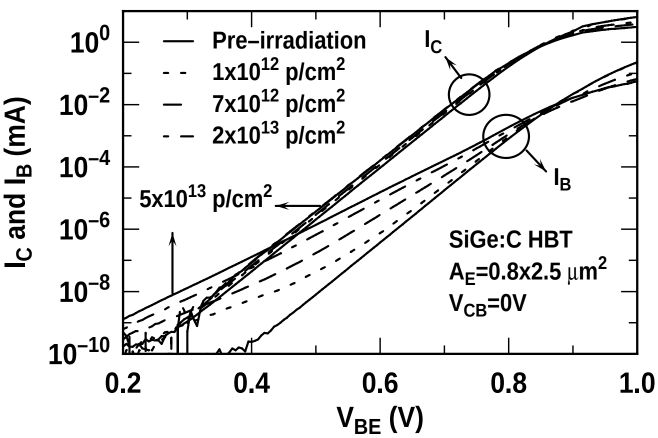

Fig. 3. Forward Gummel characteristics of the SiGe:C HBTs for pre-irradiation and four proton fluences.

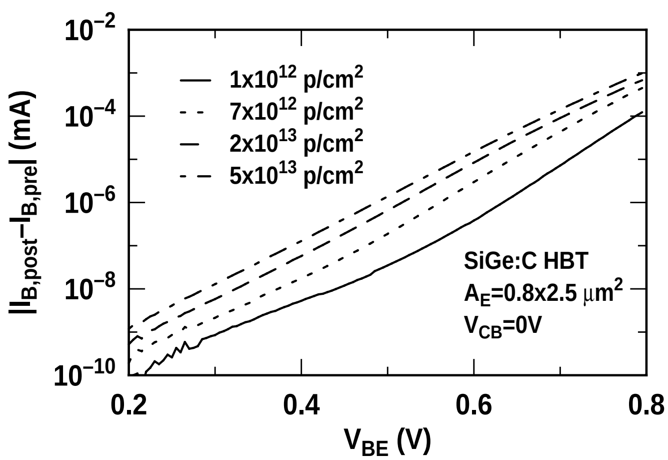

Fig. 4. The excess base current as a function of V_{BE} for the SiGe:C HBTs for four proton fluences.

Fig. 5 shows the excess base current density for 5×10^{13} p/cm^2 versus the P/A ratio for two SiGe:C HBTs with different geometry at three different V_{BE} values. The positive slopes of these curves indicate that there is a strong perimeter component to the excess base current, consistent with ionizing radiation damage of the EB spacer oxide. Our previous study on SiGe HBTs [9] indicates that surface recombination near the emitter-base spacer oxide at the emitter-base space charge region was a dominant damage mechanism for the base current degradation after proton irradiation, and we believe that this is most likely the case for this technology as well.

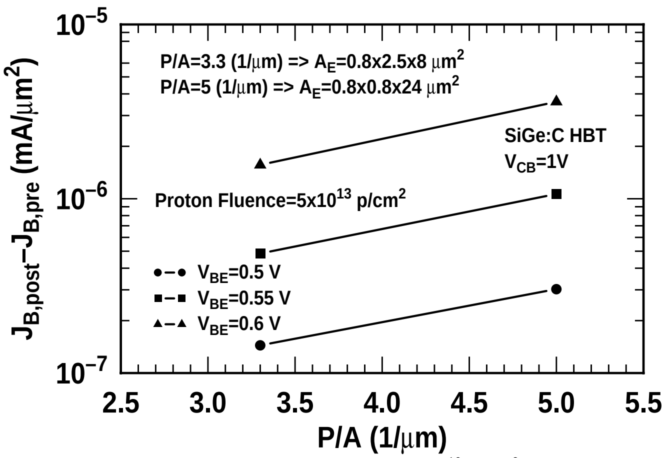

Fig. 5. The excess base current density for 5×10^{13} p/cm^2 as a function of the P/A ratio for two SiGe:C HBTs with different geometry at three different different V_{BE} values.

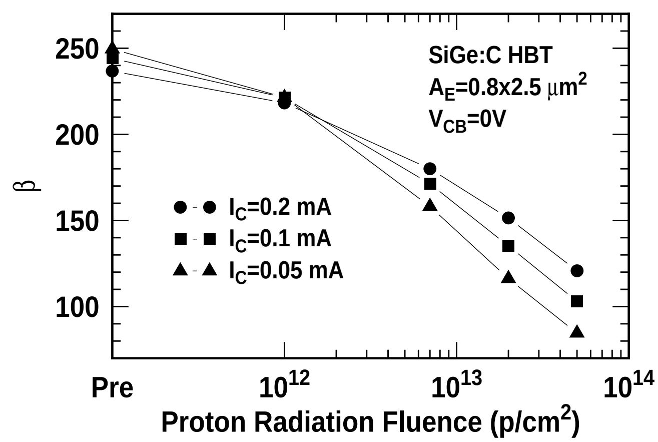

Fig. 6. The current gain as a function of proton fluence at three different biases for the SiGe:C HBTs.

Fig. 6 shows the resultant current gain as a function of proton fluence at three realistic bias currents for these SiGe:C HBTs. As expected, the current gain degrades with increasing proton fluence, since the base current increases rapidly under proton exposure and the changes of collector current I_C are relatively small. After 5×10^{13} p/cm^2 irradiation, the current gain decreases from 237 to 121 at I_C=0.2 mA, a 50% degradation. Note, however, that this value of current gain is still large enough for many circuit applications.

Fig. 7 shows the inverse Gummel characteristics of these SiGe:C HBTs as a function of fluence. Under inverse mode operation, the physical collector-base junction acts as the injecting emitter-base junction, and thus non-ideality in the inverse mode base current can be used to deduce the physical location of the proton-induced traps [9]. In inverse mode, the base current first increases with proton fluence until about 2×10^{13} p/cm^2, after which it no longer increases, suggesting a saturation of G/R trapping center generation deep inside the device near the physical collector-base space charge region. During irradiation, the inverse mode base current ideality factor increases from 1.0 to 1.55, again suggesting that proton-induced G/R centers are responsible for the observed increased base current. Fig. 8 illustrates the inverse mode excess base current versus V_{BE} for the four proton fluences. Like the forward mode results, the inverse mode excess base current ideality factor also lies between 1 and 2, suggesting that both G/R trapping centers in the bulk at the collector-base space charge region and G/R trapping centers near the surface of LOCOS oxide at the collector-base space charge region are responsible for the degradation of the base current after proton irradiation. We believe that the surface recombination near the LOCOS oxide at the collector-base space charge region is likely the dominant damage mechanism, which needs to be confirmed by studying several SiGe:C HBTs with different collector areas (layout difference).

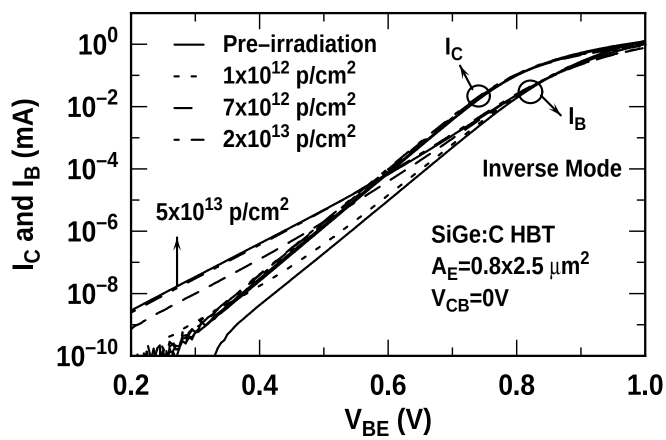

Fig. 7. Inverse Gummel characteristics of the SiGe:C HBTs for pre-irradiation and four proton fluences.

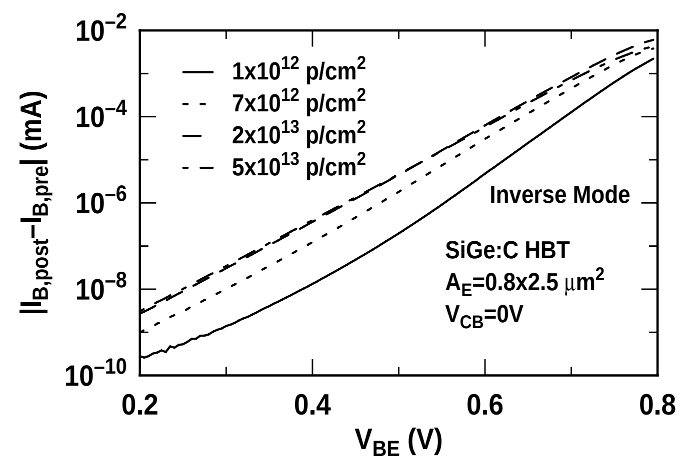

Fig. 8. The inverse mode excess base current as a function of V_{BE} for the SiGe:C HBTs for four proton fluences.

Interestingly, by comparing the inverse mode and forward mode degradation results between 2×10^{13} and 5×10^{13} p/cm^2, we can see that the base current at high fluence saturates for the inverse mode but not for the forward mode operation.

From our previous investigation [9], we know that ionizing radiation damage due to the charged nature of the proton flux will produce interface states and oxide trapped charges in the spacer oxide layer near the emitter-base space charge region. In the forward mode, as the proton fluence increases up to 5×10^{13} p/cm^2, the base current does not saturate, presumably due to the possibility of continuous damage with increasing fluence at the SiO_2/Si interface in the emitter-base spacer oxide located at the periphery of the emitter-base space charge region. For the inverse mode operation, however, the mechanism responsible for the observed base current saturation at high fluences is not obvious. We speculate, as suggested first in [10], the observed base current saturation is consistent with a mechanism, which suggests that further increases in oxide charges push the peak of the recombination rate from the surface (LOCOS SiO_2/Si interface here) into the bulk region (collector-base space charge region here) of the device. Further experiments will be required to provide evidence of this mechanism in the present devices.

To assess the radiation damage in the neutral base region in these devices (where the C doping is physically located), we have also made detailed measurements of neutral base recombination (NBR) [11]. Direct measurement of NBR in HBT's can be made by observing the change of I_B with V_{CB} at constant V_{BE}. An I_B which is a decreasing function of V_{CB} at low V_{CB} gives a clear indication of NBR. In general, for a n-p-n transistor, the base current I_B under forward-active bias is the sum of hole current injected into the emitter, electron-hole recombination current in the emitter-base space charge region, hole current due to impact ionization in the collector-base region, and the NBR component [12]. For small values of V_{CB}, the hole current due to impact ionization in the collector-base region is negligible and I_B is dominated by the other three components. The NBR component of I_B is proportional to the total electron charge injected into the base region (Q_{nB}) and inversely proportional to the electron lifetime in the neutral base region (τ_{nB}) [12]. For SiGe HBTs, the NBR component will increase compared to a comparably designed Si BJT due to an increase in Q_{nB} resulting from the Ge-induced bandgap offsets in the base region. It has been shown that the addition of C has no deleterious effects on NBR components in unirradiated SiGe:C HBTs [11].

Fig. 9 shows the normalized I_B as a function of V_{CB} at V_{BE}=0.7 V for the SiGe:C HBTs as a function of fluence. It can be seen that while the NBR in the virgin transistor is minor, the NBR component increases slightly after 1×10^{12} p/cm^2 irradiation, and as the proton fluence rises further, the NBR component becomes stronger. As shown in Fig. 2 (the SIMS profile), the base doping is very high and the base width is thin in this technology, so the change of the total electron charge injected into the base region (Q_{nB}) should be small after proton irradiation. Therefore, the degradation of the NBR component after irradiation is mainly due to the reduction of the minority carrier (electron) lifetime in the base, which is due to the proton-induced displacement damage [6].

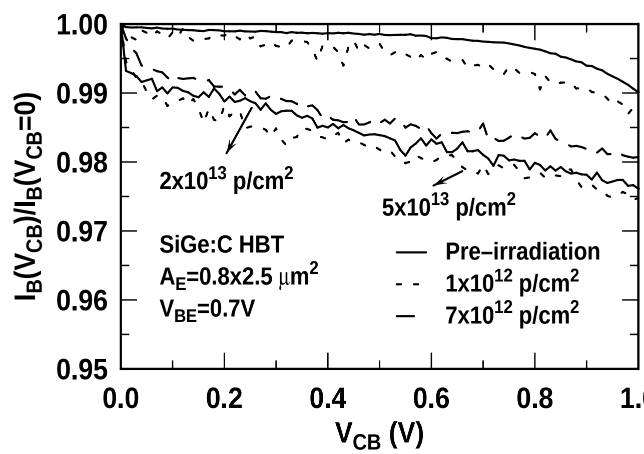

Fig. 9. Normalized I_B as a function of V_{CB} for the SiGe:C HBTs at V_{BE}=0.7 V at 300 K for pre-irradiation and 5×10^{13} p/cm^2.

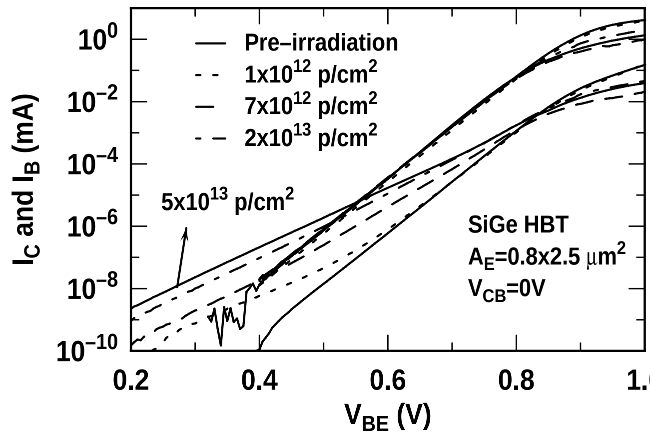

Fig. 10. Forward Gummel characteristics of the SiGe HBTs for pre-irradiation and four proton fluences.

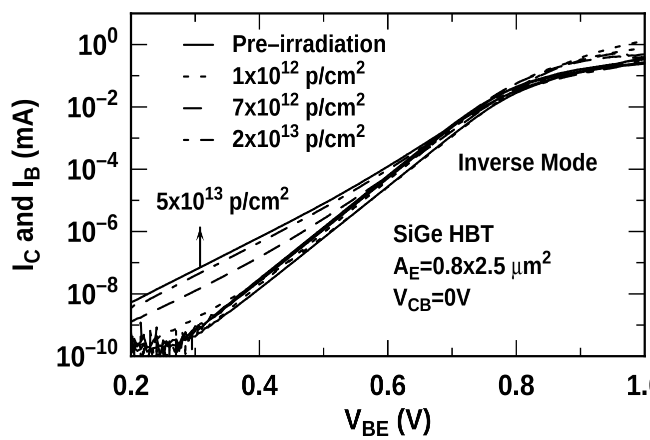

Fig. 11. Inverse Gummel characteristics of the SiGe HBTs for pre-irradiation and four proton fluences.

The relevant question in the context of these devices are: 1) to what extent are these proton results influenced by the presence of C in the SiGe base? 2) Was stronger NBR after irradiation affected by the C doping? To answer these questions, we have compared the results of the SiGe:C HBTs with those of SiGe HBTs fabricated in the same technology. Fig. 10 and Fig. 11 show the effects of proton irradiation on the typical dc characteristics of SiGe HBTs. It can be seen that at least qualitatively, the effects of proton irradiation on the SiGe:C HBTs and the SiGe HBTs are similar. Fig. 12 compares the base current of SiGe HBTs and SiGe:C HBTs for pre-irradiation and 5×10^{13} p/cm^2. It is clearly shown that the base currents for SiGe HBTs and SiGe:C HBTs are very close for both pre-irradiation and 5×10^{13} p/cm^2, suggesting that the presence of carbon does not negatively impact the radiation tolerance.

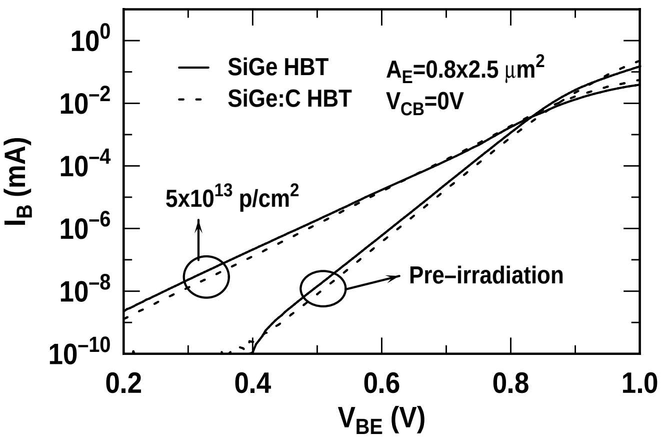

Fig. 12. Comparison of the base current between the SiGe HBTs and the SiGe:C HBTs for pre-irradiation and 5×10^{13} p/cm^2.

Fig. 13 shows the normalized I_B as a function of V_{CB} at V_{BE}=0.7 V for the SiGe HBTs for pre-irradiation and 5×10^{13} p/cm^2. Comparing this data with Fig. 9, we can see that the increase of NBR is very similar for the SiGe:C HBTs and SiGe HBTs after irradiation, indicating that C does not make the NBR worse in the SiGe:C HBTs. Therefore, we conclude that the significant degradation of these SiGe:C and SiGe HBTs under proton exposure is most likely the result of the structural features of this technology (e.g., the emitter-base spacer, and the LOCOS isolation), and not due to the aspects of the Ge incorporation or C doping. This is consistent with our previous work comparing SiGe HBTs and Si BJTs [7].

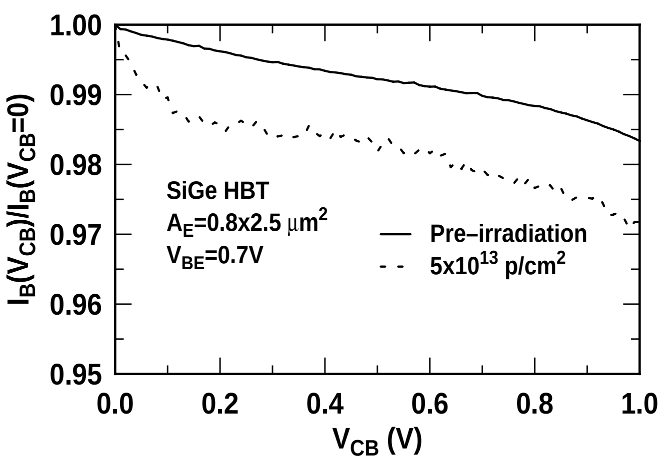

Fig. 13. Normalized I_B as a function of V_{CB} for the SiGe HBTs at V_{BE}=0.7 V at 300 K for pre-irradiation and 5×10^{13} p/cm^2.

IV. Summary

The dc characteristics and neutral base recombination of SiGe:C HBTs were investigated for proton fluences up to 5×10^{13} p/cm^2. After exposure to a proton fluence of 5×10^{13} p/cm^2, a large G/R-induced current and strong neutral base recombination is observed for these SiGe:C HBTs. The main degradation mechanism is associated with G/R trapping centers in emitter-base space charge region and bulk traps in the neutral base. A comparison of these SiGe:C HBTs with SiGe HBTs fabricated in the same process lot suggests that this proton-induced degradation is not associated with the presence of C in the base region of these transistors.

V. Acknowledgment

We would like to thank L. Cohn, B. Kauffman, K. LaBel, J. Dudenhoefer, H. Brandhorst, and the SiGe:C team at IHP in Germany for their contributions to this work, as well as T. Sanders and D. Hawkins for experimental support.

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